Reliability Roadmap for Microstructures and Micromechanical Systems

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Abstract:
Reliability and quality issues are two of the main bottlenecks choking the effective commercialization of microsystem technology. We see these same inhibitors to the commercialization of "micro" devices at JPL where the identification of failure and degradation mechanisms is essential to the building of ultra-reliable "micro" spacecraft.

JPL has successfully applied coherent design and qualification methodologies to build ultra-reliable robotic spacecraft by exploiting knowledge of the failure and degradation mechanisms of macro-sized, essentially obsolescent, structures and systems. But, the days of macro spacecraft are over. Future spacecraft/sciencecraft will be made up of ultra-reliable microstructures and MEMS sensors and actuators.

The building of ultra-reliable "micro" spacecraft requires the identification of failure and degradation mechanisms – the same inhibitors to the commercialization of "micro" devices. JPL identified this synergy with industry and established a consortium to focus on resolving these technological issues.

Manufacture of reliable microstructures and MEMS devices requires stable, mature and large-scale production programs. None of these criteria are met in the ultra-low volume fabrication typical of NASA and other research establishments. JPL is researching these product assurance issues with devices supplied by industrial consortium members.

The cost of MEMS development and ultimately the reliability of MEMS is adversely affected by the many design iterations required to characterize the physical properties of materials and to 'tune' the physical structure of devices with respect to these properties. The consortium has identified the need for, and is consolidating sponsorship to produce handbooks on "MEMS Quality and Reliability" and "Strengths of Materials."

Testing of MEMS devices is a major cost for the industry and testing protocols and techniques are crucial in accelerated life test validation. JPL is applying its environmental testing expertise to the development of new stress testing procedures and systems. Traditional product assurance and failure identification mechanisms of Atomic Force Microscopy (AFM), micro X-ray, ultrasonic microscopy and Scanning Electron Microscopy (SEM) are being applied to fracture, wire bond, structural faults, debris, and delamination analysis.

An outline of the consortium's programs and sponsorship consolidations will be presented in the form of a predictive roadmap. Finally a strategy for extending the scientific and engineering expertise of JPL and consortium members to small MEMS companies and research establishments will be addressed. A goal is to contribute to US industrial competitiveness

in the burgeoning microstructures and micro-mechanical systems market.

Introduction:

The Jet Propulsion Laboratory (JPL) is a Federally Funded Research and Development Center (FFRDC) that is managed by Caltech for NASA. The talents of a staff of 6000 world class engineers and scientists are sustained by a billion dollar budget in the utilization of NASA's 177 acre facility, plant, equipment. JPL's charter is "to go where no-one has gone before" with the responsibility of building and operating the Nation's robotic space craft, of managing and maintaining the Deep Space Network, and of making technological contributions in the National interest.

To build and integrate reliable spacecraft it is necessary to understand failure and degradation mechanisms. JPL has, for nearly 50 years, successfully applied coherent design and qualification methodologies to identify the critical parameters, methods and tools required for the ultra-low volume manufacture of ultra-reliable, macroscopic and mesoscopic spacecraft. The Cassini spacecraft, the size of a bus and near two tons in weight, was the last of the 'Battleship Galactica'. No more can the Nation afford the cost of building and launching such huge craft. In the new millennium spacecraft/sciencecraft must be of low mass and density which necessitates their being made up of ultra-reliable micro-structures and MEMS sensors and actuators.

JPL has been tasked with establishing the reliability of MEMS devices targeted for deployment on micro-spacecraft but the **ultra-low volume** manufacture by NASA or other research establishments precludes **proof of process** assurance. The building of ultra-reliable micro-spacecraft requires the identification of failure and degradation mechanisms. These are the same inhibitors to the commercialization of "micro" devices. Assurance of MEMS requires thorough process validation, proof of process build and detection by inspection - all procedures requiring stable, mature and large-scale production programs.

The environments that a planetary or deep space robot must endure encompass: temperatures of absolute zero to atmospheric entry; acceleration of launch, vibration to decelleration during atmospheric and planetry penetration; pressures from hard vacuum to hundreds of atmospheres of dense corrosive fluids. MEMS transducers produced for automotive, display and medical applications must operate, while not as severe as space applications, in the most arduous Terrestrial environments and have high reliability. These MEMS producers also have stable, mature and large scale (millions annually) production.

JPL identified the synergy between its interest in establishing the reliability of MEMS devices targeted for deployment on micro-spacecraft, and in both making the US MEMS industry competitive and accelerating the growth and acceptance of commercial MEMS. The major MEMS producers demonstrated their agreement with this synergy by joining a Quality Assurance Consortium and defining its mission to be the advancement of the commercialization of MEMS devices through:

- exchanging information
- benchmarking processes
- understanding physics of failure
- establishing design guidelines.

It is our belief that such advances will result in lower industry costs, faster time to market, and improved quality and reliability.

Consortium's Areas of Interest:

Properties of Manufacturing materials:

While many of the mechanical properties of MEMS materials are well known in their macro and bulk machined form, their properties at micro and nano scale surface machined forms are different and often unknown. Further, the decreasing geometry of MEMS structures increases the relative importance of the surface properties (surface physics) verses the volumetric properties of materials. The micro-structure and micro-morphology of the structure such as grain size, inter atomic bonds and crystalline boundaries of a material are the dominant parameters determining mechanical properties.

The importance of systematic characterization of mechanical properties of MEMS materials was recognized by the pioneers of micromachining. Each investigator built devices and, based on test results, iteratively tuned the design to obtain requisite performance. The development of new MEMS devices has been stretched considerably and many of the designs have failed because of ignorance about actual material properties.

Even for a pure bulk material such as silicon mechanical performance and fracture stress are related to fabrication techniques such as crystal growth from a high temperature melt, epitaxial growth or sputtered deposition. With compounds and polymers, mechanical properties are strong functions of deposition conditions and frequently of processes that both proceed and follow deposition. Frequently MEMS devices are created from multi-layered structures of multiple materials where each material has a different temperature coefficient of expansion resulting in room temperature stress that is a function of the fabricating process temperatures. There are also an increasing number of MEMS devices created from electro deposited metals where the physical properties and residual stress are again a function of deposition conditions.

With each individual foundry having its 'own' particular materials and with the increasing numbers of processes involved in fabricating MEMS, and particularly surfaced machined MEMS, the task of creating a comprehensive transferable materials properties catalogue is immense. In a rapid evolution technology there is also difficulty in identifying which process combinations are going to be prevalent in the next five years.

Traditionally foundries have built devices and based on performance, iteratively tuned the design and jealously guarded the 'properties' information from potential competitors. The fact that the consortium were unanimous in their desire for a transferable material properties catalogue is recognition of the great value of such a collective resource. NASA has already compiled and maintains an extensive data base on material outgassing[1] and JPL has approached, on behalf of the consortium, DARPA, NIST, SEMI and VLSI Standards seeking support for the daunting task of creating a materials properties database.

Complementary to this activity JPL has some ideas on how to characterize, both individually and collectively, the materials used in fabricating a MEMS device by direct on the wafer measurements. The technique would also enable the determination of material properties at different stages of their fabrication - a powerful diagnostic tool. The wafer test structures and mechanical measuring techniques will enable the generation of a materials database for a particular foundry and process. The consortium members would then be encouraged to pool their databases, research anomalies and make decisions on the utility of filling in any 'gaps' in the database. The details of the mechanical measuring techniques and micro test structures will be disclosed at a future date.

MEMS Quality and Reliability Handbook:
In addition to the properties of manufacturing materials the consortium had general consensus on the need for a 'MEMS Quality and Reliability Handbook'. The contents of the handbook is to cover the spectrum of technologies and practices that the MEMS production engineer needs to be familiar with. From processing definitions to statistical process control; from the physics of MEMS and structural components to the monitoring of incoming materials; from wafer processing to packaging; and from the testing of

[1] (http://misspiggy.gsfc.nasa.gov/og/)

prototypes and production devices to the determination of reliability.

Members committed to submitting material for relevant topics and elected JPL to be responsible for coordinating the activities and subsequently editing the handbook. As with material properties, NIST, SEMI and VLSI Standards have been approached for support in undertaking this activity.

GenericTester:
For all semiconductor testing electrical stimuli is mature and temperature testing stimuli well understood. In the case of MEMS, in addition to the electrical and generally the temperature stimuli, there is an additional physical stimulus and the need for the transduction of this measurand through the transducer housing. The pertinent measurand parameters are offset, sensitivity, linearity error and hysteresis as well as the dependent variable (i.e. temperature, magnetic field etc.) coefficients of offset, coefficient of sensitivity and hysteresis. The combinatorial testing load for the MEMS transducer increases factorially, over that of temperature and voltage characterization for semiconductors, for each additional physical variable. Further, the contemporary trend of hybridizing MEMS transducers with CMOS analog and/or digital logic to create *smart sensors* results in both transducer and sensor output domains that need to be separately measured and correlated. This is equivalent to an additional variable. Clearly the testing of MEMS is challenging even for single devices but the tasks escalates dramatically in complexity and cost for the 'ganged', simultaneous testing of multiple devices.

High volume production testing stations can cost millions of dollars and testing costs for a transducer can be as high as a third of its selling price. The major components of these test stations are common with physical stimulus and module fixtures changing for different measurands (pressure, acceleration etc.). Such modular testing platforms are a common requirement for the industry.
The consortium is considered an appropriate forum to refine and consolidate a specification for this equipment and SEMI; probably the organiza-tion most likely to support the activity.

Prediction of Failure Mechanisms:
In order to gain understanding of a fracture process occurring at the boundary of two dissimilar materials, when the mismatch of elastic moduli is of paramount importance, it is common to subject a specimen to a fracture test and then perform the so-called "post-mortem" evaluation of the fracture surfaces. Due to unique dimensions and properties of micro-structures and in view of their various adhesion/cohesion and geometrical configurations it is appropriate to subject the dynamic member to a fracture test under pre-determined loading and environment conditions. Following such a test a fractographic examination, involving skillful use of microscopy, should reveal a number of details and patterns which are a record of the various mechanisms and modes of fracture.

Understanding these intricate details, in turn, should lead to a better design that utilizes a combination of materials and geometries which offset the influence of the factors which induced the brittle failure. The primary tools for this investigation are the electron and atomic force microscopes (not excluding at this stage some optical magnifying devices) to observe the topographical details on the uncontaminated surface of freshly generated fractures. Available 3D graphics software (similar to the routines used in SOAP '98) would be used to process these data to better reveal certain characteristic patterns such as river marks and Riedel lines which are typically associated with rapidly propagating fractures.

Many consortium members have expressed interest in exploring micro topographical analysis as an identifier of root-cause-of-failure and as an indicator for failure corrective action and paths to improvement. Currently exploratory investigations are being undertaken on various of the consortia's mechanical affect transducers (i.e. accelerometer and pressure sensors). Pending success the techniques will be expounded and the program expanded to include more of the consortium members and more transducers.

Mechanical Shock:

Dynamic mechanical stress testing involves dropping packaged parts from various heights, different orientations and for different numbers of cycles. Statistical failure analysis is then applied to the failed populations in an effort to identify failure modes from shock energy and number of stress cycles. None of the consortium are happy with this drop test and would much prefer a controlled dynamic stress (shock) test methodology that was measurable, repeatable and a more direct cursor of failure modes.

JPL has extensive experence in mechanical stress testing methods that extend from shaker synthesis to resonant plate and pyro shock techniques. In the resonant plate technique advantage is taken of the fact that a stiff, free-free metal plate can exhibit very high frequency resonances. The article to be tested is mounted to a steel plate that is suspended in mid-air. A metal pendulum is then swung into contact with the plate, inducing transient vibration. JPL has created a hybrid resonant plate - pyrotechnic simulator. This Mechanical Impulse Pyro Shock (MIPS) tester encapsulates the basic resonant plate shock test parameters in a single, relatively compact machine where the plate is excited into resonance by the impact of a pneumatic actuator on a moveable bridge rather than by a pendulum. The MIPS shock pulse is tailored by adjusting the dimensions of the resonant plate, the strike location of the hammer, the hammer material, the size of the hammer head, and duration of applied pulse.

MIPS, tailored to the shock energies and spectrums required of different transducers, would have vastly superior dynamic stress characteristics to the drop test. Further, the shock spectrum can be measured, transducer data can be measured during test and multiple transducers can be tested simultaneously.

At the next consortium workshop JPL will demonstrate the superiority of this mechanical shock test. For those members who want to begin such testing, JPL will help design specific MIPS and resolve how best to correlate its failure assurance with that of the conventional drop tests.

Degradation:

<u>Absolute pressure:</u>

The long term stability of absolute pressure transducers is, in large part, determined by the stability of their internal vacuum. As the period of performance increases (already ten years for the automotive industry and longer for space applications) the measurement of leak-rate and hysteresis become increasingly difficult. Sensor material outgassing, 'getter' material's characteristics, hermetic seal integrity and porosity of sensor materials are all stability determining parameters.

Absolute pressure measurement is dependent on so many variables (which are themselves functions of other parameters such as temperature and thermal history) that we believe there is need for a long term stability model. JPL proposes working with consortium members to develop models for each of their transducers. This will involve working with each members' sensors measuring internal volume, hermetic seal quality (possibly by helium leak detection), outgassing of constituent materials, evaluation of getters and measurements of porosity of diaphragm etc.

JPL has started this program by undertaking fractographic analysis of glass frit-silicon bonds. This work will be followed by hermetic seal tests before starting 'modeling' and expanding activities to cover all of the consortium's absolute pressure transducers.

Micro-Relays:
Several consortium members are producing micro-relays. The reliability quotient for a relay is the number of switching operations and/or the period of time for which the 'closed' resistance remains below a specified value. Often the contact resistance of a relay increases, and the relay 'fails', without showing any obvious degradation of the contact surfaces. Switching load and contact materials are obvious factors but the environmental gasses have also been found to play a significant role.

JPL plans to use electron and atomic force microscopes to undertake detailed topographical analysis of contact surfaces. SEM secondary electron spectroscopy will attempt the identification of surface contaminants and chemical gas or mass spectrographic analysis will be made of dissolved or scrapped off (AFM) surface contaminants.

Micro-relays have great potential for space applications such a motor commutation, instrument multiplexing, phased array antennas and eventually radiation hard digital logic (when speed and switching life are large enough). JPL is waiting on the supply of failed relays to enthusiastically embark on this program.

Accelerated Life Testing:
Accelerated life testing is crucial in determining the long term reliability of devices. With spacecraft life times in the decades and with automobile parts warranted for 100,000 miles and a decade, the operational life time of a device already exceeds its design and fabrication time many times over. Accelerated life testing is mandatory.

The principal problem with accelerated life testing is applying realistic stressing that correlates with the survivability and/or degradation of a device while not invoking extraneous failure mechanisms. Electrical diagnostic and screening tests, and in some cases trimming, are undertaken on the wafer as a first level assurance qualification. Mechanical stimulus of a sensor's (effector's) measurand is not done until after dicing and packaging. Typically, mechanical burn in is the second screening level for parts that have survived the mechanical traumas of dicing, ultra-sonic bonding and packaging; possibly electrostatic trauma and the shock (quiescent) of transport. The next screening level involves the systematic stressing of the transducer (an accelerometer for example) by voltage cycling, temperature cycling, drop testing and autoclave cycling.

The reliability assessment for the device is then determined by the analysis of failures and failure rates for each testing level. This quality assurance procedure is typical of the industry and universally recognized as inadequate.

JPL has conceived of a means of applying mechanical affector stimulus directly and individually to each sensor on a wafer. Electrical and mechanical 'probing' can provide diagnostic testing, screening and infant mortality discrimination before dicing and packaging. However, we believe the techniques are even more powerful in allowing the direct measurement of each device's Young's modulus, bulk density and structural damping. Extensive mechanical burn in (life testing) of transducers is also provided by operating the device at resonance for extended periods.

New technology disclosures are under preparation and revision. We believe that industry will be easily convinced of the economics of additional pre-package screening and the potential of a rigorous 'accelerated life testing' technique.

At the next consortium workshop JPL will attempt convincing industrial members of the utility of funding the implementation of these techniques in their respective fabrication facilities. An accurate 'accelerated life testing' predictor of reliability is the 'Holy Grail' for determining the technology readiness levels (TRL) of micro spacecraft components.

Logistics:
JPL has NASA funding for the direct determination of the reliability of microstructures and MEMS devices. The fractographic analysis of structurally failed devices and the failure analysis of micro relays are, as yet, the only programs the consortium have defined that directly relate to the determination of reliability and complement industrial practice. For these programs industrial members supply their components, JPL undertakes the analysis, reports the results (only to a specific member) and generates a confidential NASA report.

The majority of programs are less directly associated with reliability and generally more tightly related to a specific members' devices. To participate in these programs the consortium members have joined the Technologies Affiliates Program (TAP) to collectively or individually contract JPL to task its various experts to undertake specific research. The outcome and reports of these contracts are held confidential with contracting organization.

For the infrastructure programs of material properties, MEMS quality and reliability handbook and generic tester we have looked to the responsible National (or international) organizations for collaboration and fiscal support.

JPL's impartiality, commercial non-competitiveness and confidentiality were attributes that enabled the formation of this consortium of major MEMS producers. Experience with other technology consortia have demonstrated high synergy and enabled the execution of more far reaching programs than could have been afforded or fielded alone. It is our hope that this can be repeated in the MEMS technology sector. To date, consortium members have not identified a cooperative program but have tacitly agreed to provide sanitized information to NASA (for non-TAP activities) and to strive to release information to the consortium and hopefully the broader MEMS community.

Fledgling MEMS community:
MEMS quality assurance is only going to be determined from stable, mature and large scale production which excludes MEMS laboratory developers and fledgling MEMS foundries. This fledgling MEMS community does not have the diagnostic measurement and testing tools, or the experienced operators, that the large mature MEMS producers or National laboratories do.

Expert assistance would shorten development cycles, resolve fabrication problems and generally improve competitiveness. JPL's secondary charter of making technological contributions of National interest incompasses the shepherding of a fledgling MEMS community. Such a program may be implemented by the community becoming members of the JPL Technology Affiliates Program. While TAP membership is not consortium membership the utility of technological assistance would be invaluable to these fledgling producers. It would accelerate them into the stable, mature and large scale production regime from where they could join the consortium.

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